# SPS AND LEP STATUS REPORT

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ABSTRACT

Driven by the needs of the neutrino experiments, the intensity of the SPS proton beam has considerably increased during the past years, with a maximum of 4.8 x $10^{13}$ protons per pulse accelerated to 450 GeV/c. This progress was achieved by an improved quality of the injected beam as well as improved operational procedures.

The heavy ion programme of the SPS has been continued since 1994 with the acceleration of fully stripped lead ions $Pb^{82+}$ to 158 GeV/c per nucleon. Fixed frequency acceleration at the beginning of the cycle is followed by acceleration using a normal synchronous frequency programme. This procedure results in a good spill quality of the extracted ion beam while coping efficiently with the relatively low $\beta$ of the lead ions at injection.

A new extraction channel which will be installed in the SPS for the transfer of 450 GeV/c protons to the LHC, opens the option of a neutrino beam to the Gran Sasso laboratory in Italy, 732 km away from CERN. The conceptual design of this beam will be described.

The energy of CERN's flagship, the large electron-positron collider LEP has been raised in several steps since 1995, following the installation of an increasing number of superconducting RF cavities. At present, a total of 272 superconducting cavities are in operation with an average gradient of 6 MV/m. This allows relatively comfortable operation of LEP at an energy of 94.5 GeV per beam. After the installation of 16 additional cavities and an increase of the gradient to values close to 7 MV/m it is hoped to reach a beam energy of up to 100 GeV during the years 1999 and 2000, the last years of LEP operation. The performance of LEP and its limitations will be discussed.

## 1. SPS FIXED TARGET OPERATION WITH PROTONS

A typical supercycle for SPS fixed target operation with protons is shown in Fig.1. A 450 GeV/c proton cycle is followed by two lepton cycles during which positrons and electrons are accelerated from 3.5 GeV to 22 GeV for injection into LEP. The second of these cycles, the electron cycle, is extended, presently to a 26 GeV/c plateau for proton injection, in order to permit extensive machine studies related to the preparation of the SPS as an LHC injector and of the LHC itself.

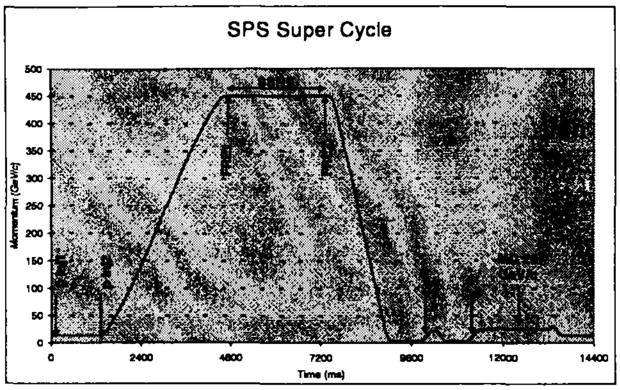


Fig.1: A typical SPS supercycle.

For the high energy proton cycle, two batches of protons, some 10 μsec long each, are delivered by the PS complex for injection into the SPS at 14 GeV/c. The beam is then accelerated to 450 GeV/c, extracted and sent onto external targets. Two fast half-integer resonant spills with a duration of 4 to 6 msec are provided for CERN's present neutrino programme. Nearly rectangular spills have been achieved by a suitable control of the capacitor discharge current through the quadrupole which excites the resonance [1]. The fast resonant bursts are separated by a slow third-integer extraction of some 2.5 sec duration during which the protons are simultaneously shared between two extraction channels serving the two experimental areas of the SPS.

Since 1994 the intensity of the SPS proton beam has increased from the previous maximum of 3.5 x $10^{13}$ protons per pulse to 4.8 x $10^{13}$ ppp, a record intensity reached in 1997. This progress in performance was achieved by a number measures of which the following should be mentioned:

- The intensity of the beam in the injector complex was raised up to a maximum of 3 x $10^{13}$ protons per PS cycle accelerated to 14 GeV/c. At the same time, the beam quality from the PS improved, resulting in particular in a smaller emittance of the injected beam and in a more even distribution of protons along the SPS circumference, thus avoiding harmful peak intensities in cavity like objects;
- The vertical aperture of the SPS was continuously monitored and machine components realigned or even exchanged when necessary, leading to an

increase of the aperture from 21 mm to 37 mm (normalized to $\beta_{max}$ of 107 m);

- The closed orbit correction was extended from 14 GeV/c to 50 GeV/c;
- During proton acceleration, the superconducting cavities which are used during the lepton cycles, were damped more efficiently by completing the RF feedback system with a feedforward loop and a one-turn feedback [2].

These measures combined with a good reliability of the injector chain and all the SPS machine components (the overall efficiency reached values close to 80%) resulted in record integrated intensities during the last years, with a maximum of 2.3 x $10^{19}$ protons on the external targets during a one year period. In Fig.2 , the integrated numbers of protons delivered to all targets as a funtion of time are compared for the different years since 1993.

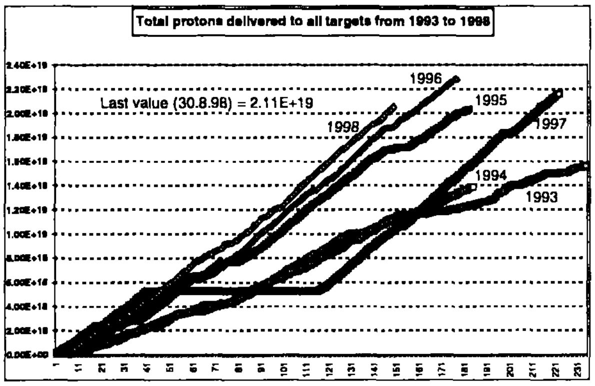


Fig.2: Integrated number of protons for the years 1993 to 1998 (Note that the 1998 run will continue for another 3 weeks).

Most of the accelerated protons, up to some 3.5 x $10^{13}$ protons per cycle, have been extracted in the fast resonant mode described above and used for neutrino physics. The protons extracted during the slow spill have been used to feed a number of targets from which different secondary beams are derived. Currently, most of these secondary beams serve as test beams for the preparation of the various components of the huge and complex LHC detectors which are under construction.

However, some physics experiments, in addition to those of the neutrino programme, are still performed during SPS fixed target operation with protons. The secondary $K^0$ beams for one of these experiments which aims to study direct CP-violation, will briefly be described since a novel application of a bent silicon crystal is made to achieve beam splitting [3].

In order to minimize systematic differences in the relative measurement of two-$\pi$ decay rates of long- and short-lived neutral kaons, $K_L$ and $K_S$ beams are required to enter the same fiducial region simultaneously and nearly collinearly, converging at a small angle towards a common set of detectors.

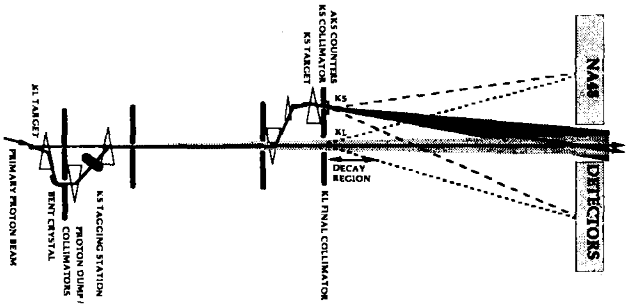


Fig.3: Schematic layout of $K^0$ beams.

The layout of these simultaneous $K_L$ and $K_S$ beams is shown schematically in Fig.3. The 450 GeV/c primary proton beam hits the $K_L$ target under a small vertical downward angle. The target is immediately followed by a copper collimator through which the neutral $K_L$ and the remaining proton beams exit. A vertically deflecting dipole magnet serves to sweep away charged particles, whereby the primary protons are deflected further downwards. They impinge on a bent crystal, centred some 72 mm below the $K_L$ beam axis. The crystal is designed to split off a small fraction of the protons by deflecting them through an upward angle of 9.6 mrad, back to the horizontal. The crystal fulfills the following vital functions:

- It splits off the desired small fraction (~ 5 x $10^{-5}$) of the protons coming from the $K_L$ target;
- It defines small emittances of the bent low intensity beam in both the horizontal and vertical planes;
- It cleans the beam from all secondary particles.

Eventually, the low intensity proton beam emerging from the crystal hits the $K_S$ target, located 72 mm above the $K_L$ beam axis. Both the $K_L$ and $K_S$ beams enter the common fiducial region and intersect each other at the experiment at a relative angle of 0.6 mrad. A Tagging Station placed in the proton beam between the crystal and the $K_S$ target allows to distinguish whether an observed $K^0$ decay originated from the $K_S$ beam, by measuring the time of flight between this station and the main detectors of the experiment.

The $K^0$ beams are now used for physics data taking and have performed according to specification.

## 2. SPS FIXED TARGET OPERATION WITH LEAD IONS

Since 1994 the SPS has been used for the acceleration of fully stripped lead ions $Pb^{82+}$ to 158 GeV/c per nucleon (equivalent proton momentum: 400 GeV/c) during a period of some 5 to 6 weeks per year

[4]. After slow resonant extraction, the high energy ions are directed towards external targets with the aim to create a quark-gluon plasma. A number of different experiments have been conceived to detect the signature of such a plasma, like strangeness enhancement or J/ψ suppression.

The lead ions are injected into the SPS at a momentum of 5.1 GeV/c per nucleon. The change in revolution frequency during acceleration is much larger than can be accepted by the existing 200 MHz travalling wave cavities with their limited bandwidth. A technique has been developed to overcome this limitation [5]. It takes advantage of the relatively short filling time of the cavities and the fact that the beam is grouped in four 2 μsec batches (injected at 1.2 sec intervals), separated by 3 μsec gaps. The cavities can therefore be powered at their optimum frequency and the structure is emptied between the passage of successive batches and re-filled with the appropriate phase, such as to maintain the synchronism during acceleration.

In 1994, this fixed frequency (non integer harmonic number) acceleration was maintained up to top energy. The beam remained grouped in 2 μsec batches and the resulting spill structure during resonant extraction turned out to be very inconvenient for the experiments. For this reason, in 1995 a plateau was introduced at 10 GeV/c per nucleon as shown in Fig. 4.

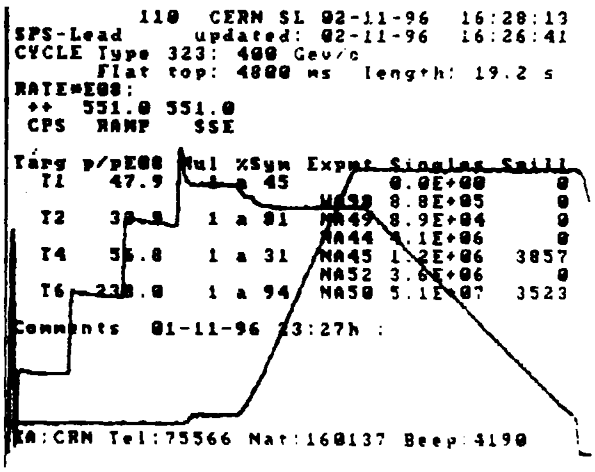


Fig.4: Main dipole field and lead ion intensity during the SPS cycle.

On this plateau the beam is debunched and recaptured. It is then accelerated using a normal synchronous frequency programme. In this way the 2 μsec structure is very much reduced at extraction and the effective spill duration increased by a factor of three.

The intensity of the accelerated lead ion beam has steadily improved since the programme was started. During 1996 a peak intensity of $8 \times 10^8$ ions per pulse at 158 GeV/c was reached. The best beam transmission in the SPS was 81%, with losses mainly occuring at injection and during the two RF captures.

After another run at high energy in 1998, the lead ions are likely to be accelerated in 1999 to a maximum momentum of 40 GeV/c per nucleon only in order to allow a comparison of high energy and low energy data collected by the experiments.

## 3. THE OPTION OF A CERN NEUTRINO BEAM TO GRAN SASSO

A major project has been launched to prepare the SPS for its future role as LHC injector [6,7]. In this framework, a new extraction channel will be installed in the machine which opens the option of a neutrino beam to the Gran Sasso laboratory situated underground in central Italy, 732 km away from CERN. This beam will be produced from the decay of pions and kaons created in the interaction of an intense 400 GeV/c proton beam with a graphite target. A conceptual design of the facility has recently been published [8]. Its schematic layout is shown in Fig.5.

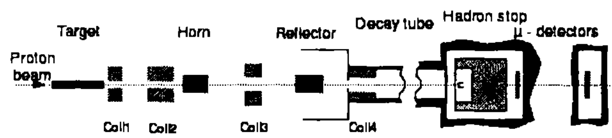


Fig.5: Components of the proposed neutrino beam.

Protons are extracted from the SPS in short intense bursts of 10 to 20 μsec duration and transported through a transfer line which is 800 m long and inclined downwards by 5.6% in order to point towards the Gran Sasso detectors. The protons hit a graphite target which consists of 11 rods, 10 cm long and 3 mm diameter each. The rods are cooled by a forced helium gas flow. Pions and kaons emerging from the target in the required energy band are focused to form an approximately parallel beam, using two magnetic coaxial lenses, called horn and reflector, of similar shape but different size. These pions and kaons decay in flight to produce muons and muon neutrinos. To avoid that the pions and kaons interact before their decay, an evacuated decay path of some 1000 m length is foreseen. The decay pipe has a diameter of 2.45 m and will be evacuated to a pressure below 5 mbar.

At the exit of the decay tunnel a massive iron dump absorbs primary protons that have not interacted as well as all secondary particles other than muons (which are stopped further downstream in the earth) and neutrinos. The muon flux distribution is measured by two arrays of silicon detectors, a first one immediately downstream of the hadron stopper and a second one installed after a 67 m thick region of rock (molasse). These muon detectors allow "on-line" monitoring and tuning of the beam.

The following performance is presently expected: Two fast bursts of 10 μsec duration will be extracted per SPS cycle at an interval of some 50 msec in order for the graphite target to cool down sufficiently after the first burst. The maximum intensity of 2.25 x $10^{13}$ protons per burst which has been assumed, corresponds to the limit of the graphite target and, for two successive bursts, nicely matches the maximum intensity of some 4.5 x $10^{13}$ protons per pulse which the SPS can safely deliver. Assuming 200 days of operation per year and an efficiency for neutrino physics of 50%, the total number of protons on target per year amounts to 3 x $10^{19}$. A rate of 1400 $\nu_\mu$ CC (charged current) events per year per kiloton of detector material is then expected in a Gran Sasso detector. The corresponding rate of $\nu_\tau$ appearance events largely depends on the assumed model and lies in the range from 0.3 to 70 events per year and kt.

## 4. PRESENT STATUS OF LEP

After its commissioning in 1989 the Large Electron-Positron collider (LEP) operated at a beam energy of 46 GeV for some six years, providing an integrated luminosity of 200 $pb^{-1}$ to each of the four experiments. Since October 1995 the beam energy has been raised in several steps, following the installation of an increasing number of superconducting RF cavities.

At present the LEP radio-frequency system consists of 48 Cu cavities, 16 superconducting cavities made of Nb sheet (nominal gradient 5 MV/m) and 256 sc Nb/Cu cavities (nominal gradient 6 MV/m), made of a thin Nb-film deposited on a copper substrate. This system provides a nomial RF voltage of 2.85 GV. While a maximum voltage of 2.9 GV has already been reached this year, the voltage routinely used for physics fills is of the order of 2.7 GV, permitting relatively comfortable operation of LEP at a beam energy of 94.5 GeV.

In order to achieve the highest possible luminosity for given beam currents, a low emittance optics is used with $102^0$ horizontal and $90^0$ vertical phase advance per cell in the arcs. A further reduction of the horizontal emittance is obtained by adjusting the horizontal damping partition number $J_x$ to values higher than 1. At the start of a physics fill, an increase of the radio-frequency by 100 Hz with respect to its nominal value results in $J_x$ = 1.56. In the middle of the fill, $J_x$ is further raised to a value of 1.68 ($\Delta\nu$ = 120 Hz).

At present, LEP is operated with four bunches per beam. At injection the bunch current is of the order of 760 μA, slightly reduced to 720 μA in physics after some losses during acceleration form 22 GeV to 94.5 GeV. With this total current $2I_0$ of 5.8 mA for the two beams, initial luminosities exceeding 7 x $10^{31}$ $cm^{-2}$ $s^{-1}$ are now regularly achieved. Inspite of a relatively high vertical beam-beam tune shift $\xi_y$ of up to 0.064, the beam-beam limit has not yet been reached. Accordingly, the luminosity decays with $(2I_0)^2$ during the fill. The lifetime during the coast is of the order of 5 to 6 hours (single beam lifetime at 94.5 GeV: ~ 35 h). Typical fills for physics therefore only last some 4 hours before LEP is re-filled, a procedure which takes between 60 and 90 minutes.

So far, the collider has proven to be very reliable this year. 83 % of the fills were dumped at the end of their useful life by the operators. Only 6.5 % were lost due to faults of the huge and complex RF system, containing nearly 10 000 RF interlocks.

In 1998, the maximum current in LEP is essentially subject to two limitations, one expected and one unexpected. The expected limit at $2I_0$ = 6.5 mA is due to beam-induced losses in the cavities exhausting, together with the RF dissipation and with the static losses of the superconducting modules, the liquid He cooling capacity at 4.5 $^0$K of the cryoplants.

The unexpected limit is given by the maximum power of 8 W which can be dissipated without damage in thin cables used to transmit the signals from small antennae. Two of these antennae are mounted in each superconducting cavity for field measurements. The cables pass through the superinsulation of the cryostat where they are insufficiently cooled. The unexpectedly high power in the cables results from the fact that the antennae pick up higher order modes induced by the beam in the small antenna ports. The losses strongly depend on the bunch length. LEP is therefore very carefully operated in a way to ensure that this length stays above 10 mm. In particular, the synchrotron tune $Q_s$ which is set to the relatively high value of 0.137 at injection in order to keep the threshold of the transverse mode-coupling instability and the required RF voltage sufficiently high, is lowered to 0.112 as soon as the beams have been accelerated to 32 GeV. Running LEP with the necessary precautions has made it possible to raise the total current above 6 mA, not far from the cryogenic limit. It is presently intended to entirely remove the limitation of the beam current brought about by the antenna cables by replacing them with low loss cables of an appropriate diameter during the 98/99 winter shutdown.

The maximum luminosity per calendar day which has been achieved so far this year, amounts to 2.5 $pb^{-1}$. During the best (sliding) 24 hours a maximum of 2.85 $pb^{-1}$ could be reached. At the time of writing this report, the total integrated luminosity at 94.5 GeV has exceeded 100 $pb^{-1}$ and LEP is well under way to reach or even surpass the 1998 objective of 150 $pb^{-1}$.

## 5. LEP PLANS AND LIMITATIONS.

In order to fully exploit the potential of LEP during its last two years of operation, 16 additional Nb-film cavities will be installed in the winter shutdown 98/99. At the same time, the upgrade of the LEP cryoplants for the LHC will be implemented so that the dynamic load capacity at 4.5 $^0$K will nearly be doubled. As a result, it will become possible to push the gradient of the Nb-film superconducting cavities beyond the design value of 6 MV/m, with the objective to attain values close to 7 MV/m. The performance of LEP which can then be expected, has been discussed in some detail in recent papers [9,10,11]. In the following, only a short summary of the expectations and limits will therefore be presented.

The gradient in the superconducting cavities is ultimately limited by field emission which in addition to creating increased cryogenic losses, gives rise to a high level of radiation leading to component damage or activation. While a significant reduction in field emission can be obtained by pulsed RF power processing and He processing in situ, an average gradient of 7 MV/m will be hard to exceed, although a big step in this direction has been done during cavity conditioning in 1998, when an average gradient of 6.8 MV/m has been reached. Further work is needed to reduce the imbalance in the fields of the individual cavities, mainly by inserting transformers in the waveguides in order to compensate the spread in performance of the power couplers.

With the present optics and $J_x = 1.5$, a gradient of 6.85 MV/m is required in the Nb-film cavities in order to reach a beam energy of 100 GeV (assuming a quantum lifetime of 24 hours). At this energy, a gradient of 7 MV/m would then offer a slight but highly desirable operational margin.

After the planned upgrade of the cryogenic plants, cavity operation at 7 MV/m will leave about 80 W of dynamic cooling power per module at 4.5 $^0$K to cope with higher order mode losses. These losses which are characterized by a resistance $R_m$ can be expressed by the equation

$$P_m = (2I_0)^2 R_m(\sigma_s) / (n_b k_b)$$

where $n_b$ is the number of beams and $k_b$ the number of bunches per beam. $R_m$ has been measured to be about 16 M$\Omega$ and to increase strongly once the bunch length $\sigma_s$ is lower than 10 mm. With 4 bunches per beam, a total beam current $2I_0$ slightly above 6 mA will then be possible at 100 GeV, a current similar to the current reached in present operation.

Fig.6 shows the luminosity limit given by the cryogenic cooling power as a function of the beam energy, together with the limits by the available RF power, the maximum vertical tune shift $\xi_y$ (assumed to be 0.055) and the transverse mode-coupling instability (TMCI). The figure also shows the lines of constant beam lifetime of 6 and 7 h which coincide with the lines of constant beam current 6 and 8 mA.

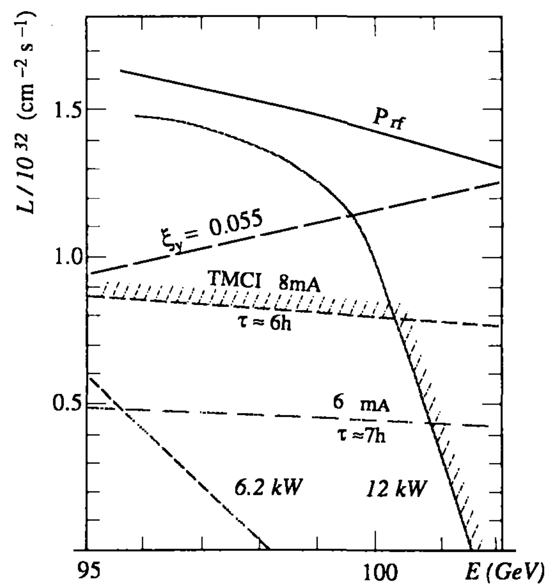


Fig.6: Limits in the luminosity-energy plane for $J_x = 1$, $k_b = 4$ and the $102^0/90^0$ optics. Parameters: $\varepsilon_{x0} = 44.4$ nm at 100GeV and $J_x = 1$, $\kappa = 1\%$, $\beta_x^* = 2$ m, $\beta_y^* = 5$ cm. Lowest hard limits are shaded.

The figure shows that peak luminosities similar to those currently achieved should be possible at 100 GeV, but also that 101.5 GeV is an upper limit, at least with the assumed optics and $J_x = 1$.

## 6. ACKNOWLEDGMENTS


I would like to thank all my colleagues for the excellent work which they have done to make the SPS and LEP operate so well and for the help in preparing this status report.


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